# Acceleration of UHE Cosmic Ray Particles
# at Relativistic Jets
# in Extragalactic Radio Sources

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## Abstract

A mechanism of ultra-high energy (UHE) cosmic ray acceleration in extragalactic radio sources at the interface between the relativistic jet and the ambient medium is discussed as a supplement to the shock acceleration in 'hot spots'. Particles accelerated at the jet side boundary are expected to dominate at highest energies. The spectrum formation near the cut-off energy is modeled using the Monte Carlo particle simulations.

## 1. Acceleration processes in relativistic jets

We extend the discussion of particle acceleration at shock waves formed in the terminal points of relativistic jets (Rachen & Biermann 1993, Sigl et al. 1995) by including the additional acceleration process acting at the jet boundary layer. For particles with UHE energies both the shock and the transition layer between the jet and the ambient medium can be approximated as surfaces of discontinuous velocity change. The tangential discontinuity considered in the latter case can be an efficient cosmic ray acceleration site if the considered velocity difference $U$ is relativistic and the sufficient amount of turbulence is present on its both sides (Berezhko 1990, Ostrowski 1990). On average, for an individual boundary crossing UHE particle gain energy is

$$< \Delta E > /E \, = \, \rho_e \, (\gamma_u - 1) \qquad ,$$

where $\gamma_u$ is the flow Lorentz factor and the numerical factor $\rho_e$ depends on particle anisotropy at the discontinuity. In the presence of efficient particle scattering, particle simulations give $\rho_e$ as a substantial fraction of unity (Ostrowski 1990). Let us also note that in the case of non-relativistic velocity jump, $U << c$, the acceleration process is of the second-order in $U/c$.

**Fig. 1** The model applied for the final part of the jet, near the terminal shock. An example particle trajectory is sketched.

## 2. The accelerated particle spectrum

Spectra of particles accelerated at relativistic shock waves depend to a large extent on the poorly known physical conditions near the shock. Therefore, in the present simulations we do not attempt to reproduce a detailed shape of the particle spectrum, but rather consider the form of spectrum modifications introduced to the *power-law with a cut-off* shock spectrum by the additional acceleration at the jet boundary. We neglect the radiation losses, i.e. the upper energy limit is fixed by the boundary conditions allowing for escape of highest energy particles.

In the simulations, we consider the shock resting with respect to the cocoon surrounding the jet (Fig. 1). The upstream plasma hitting the shock moves with the relativistic velocity $U_1$ and is advected downstream with the velocity $U_2$. The compression ratio $R = U_1/U_2$ is derived for the shock propagating in cold electron-proton plasma. The conditions arising behind the jet terminal shock due to the flow divergence are modeled by imposing a free escape boundary for particle escape at finite distance, $L_{esc}$, downstream the shock and in the front part of the cocoon adjoining this boundary. Furthermore, we introduce another, tube-like free escape boundary surrounding the jet at a distance $R_{esc}$ from the jet axis. The mean magnetic field is assumed to be parallel to the jet velocity both within the jet and in the cocoon. In the examples presented below the ratio of the *effective* cross-field diffusion coefficient to the parallel diffusion coefficient is $D = 0.13$.

**Fig. 2** Particle distributions $F(p) \equiv dN(p)/d(\log p)$, which give the particle numbers per logarithmic momentum bandwidth, for particles escaping through the boundaries. Particles with the momentum $p = 1.0$ have a gyroradius equal to the jet radius, $R_j$. The injection momentum is $p_0 = 10^{-3}$, and we take $R_{esc} = 2R_j$ and $L_{esc} = 1$ downstream diffusive scale. With shorter dashes we denote the spectrum for the front boundary, with the longer ones for the side boundary, and the full line represents a sum of the two. The dashed straight line is a power-law fit to the low-energy part of the spectrum.

At Fig-s 2,3 we consider spectra of particles escaping through these boundaries for the seed particle injection at the shock. The shock acceleration process determines the spectrum inclination due to the combined action of the particle energization at the shock and the continuous particle advection with the plasma. In the present simulations we consider fixed spatial distances to the escape boundaries, but the size of particle trajectory defined by its gyroradius, as well as the spatial diffusion coefficients, increase in proportion to particle momentum. Due to this increase, the escape probability grows with the particle momentum providing a cut-off in the spectrum. The energy scale of the cut-off is different for the shock spectrum and the side boundary spectrum, with the latter being always larger. The difference between these two scales increases with e.g. the jet velocity, the extent of the diffusive cocoon, shifting the particle injection site upstream the shock, increasing the effective particle radial diffusion coefficient. One should note that in the range of particle energies directly preceding the cut-off energy the total spectrum exhibits some flattening with respect to the inclination expected for the standard picture of the shock acceleration. There are two reasons for that flattening: an additional particle transport from the downstream shock region to the upstream one through the cocoon surrounding the jet (this effect occurs also if there is no

**Fig. 3** A comparison of particle spectra generated in jets with different velocities $U_1$ given near the respective curves.

**Fig. 4** Comparison of the spectra obtained for the far upstream seed particle injection (a, b) and for the shock injection (c, d). $R_{esc} = 1R_j$ for dashed lines (b, d) and $10R_j$ for solid lines (a, c).In all cases $L_{esc} = 1$.

side boundary acceleration ! ), and inclusion of the very flat spectral component resulting from the side boundary acceleration.

At Fig. 4 we consider particles injected far upstream the shock, in the distance $10^3 \, R_j$, at the jet side boundary. In this case the resulting distribution of particles is very flat. This feature results from the character of the acceleration process with particles having an opportunity to hit the accelerating surface again and again due to inefficient diffusive escape to the sides. The apparent deficiency of low-energy particles in the spectrum results from the fact that most of these particles succeeded in crossing the discontinuity several times before they were able to diffusively escape through the side boundary. In another words, the escape due to particle energy increase (and the corresponding diffusion coefficient increase) is much more effective than the escape due to low energy particle diffusion across the cocoon.

## References

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front boundary

$U_2$

shock

side boundary

cocoon

cocoon

side boundary

$U_1$

jet

( ↓ far upstream)